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ORIGINAL ARTICLE

Wireless charging and shared autonomous battery electric vehicles (W+SABEV): synergies that accelerate sustainable mobility and greenhouse gas emission reduction

Zicheng Bi[1] · Michael A. Reiner[1] · Gregory A. Keoleian[1] · Yan Zhou[2] · Michael Wang[2] · Zhenhong Lin[3]

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Abstract

Emerging technologies play important roles in shaping future mobility systems and impacting sustainability performance of the transportation sector in major economies, such as the United States of America (USA) and China. This study applies a life cycle framework to demonstrate and evaluate the synergies of the following four emerging transportation system technologies both qualitatively and quantitatively: (1) wireless charging; (2) shared mobility services; (3) autonomous driving; and (4) battery electric vehicles (BEV). The new concept of a wireless charging and shared autonomous battery electric vehicle (W+SABEV) system is introduced and modeled. First, an analytical framework is presented to assess the pros and cons of the W+SABEV system vs. a conventional plug-in charging BEV system, adhering to the principles of sustainable mobility and highlighting the impacts and dynamics of the disruptive technologies on the key parameters that define sustainable mobility. Second, a quantitative analysis presents the synergies of the four technologies by modeling a W+SABEV system and demonstrates that the combination of the four technologies can shorten the payback time of greenhouse gas (GHG) emission burdens for infrastructure and vehicles. Compared to a plug-in charging BEV system, a W+SABEV system pays back the additional GHG emission burdens of wireless charging infrastructure deployment within 5 years if the wireless charging utility factor (ratio of en route charging time vs. trip time) is above 19%.

Keywords Wireless charging · Shared mobility · Autonomous vehicle · Electric vehicle · Sustainability

Zicheng Bi now work at Argonne National Laboratory (zbi@anl.gov)

✉ Gregory A. Keoleian
gregak@umich.edu

Extended author information available on the last page of the article

1 Introduction

As world's two largest economies, the United States of America (USA) and China are facing significant energy and environmental burdens from the transportation sector. Both countries are working towards cleaner transportation by incentivizing and investing in vehicle electrification, automation, and connectivity, promoting shared mobility, and integrating charging infrastructure (Hao et al. 2015; Zhou et al. 2015). A new era in transportation is marked by recent dramatic transportation modal shifts, research and development (R&D) of clean vehicles and emerging technologies, and design of sustainable mobility systems. The trend is driven by three defining components: (a) a shared vehicle economy; (b) connected and automated vehicles (CAVs); and (c) vehicle electrification (Fagnant and Kockelman 2014). Each component offers a distinct set of benefits, poses a complex range of challenges, would fundamentally reshape vehicle and mobility systems, and ultimately enables a more sustainable means of moving people. To ensure a sustainable transition in transportation services, the diffusion of these three disruptive technologies requires a fundamental shift in our infrastructure in terms of the electricity grid, road systems, and the way in which vehicles are fueled or charged (Chen et al. 2016).

Charging time, vehicle driving range, and availability of conventional plug-in charging infrastructure have long been cited as barriers to electric vehicle (EV) adoption (Bi et al. 2016). Therefore, a revolution in charging infrastructure and charging ways for EVs, including plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs), is critical in shaping future sustainable transportation and impacting EV adoption and performance of both private and public fleets. Recent breakthroughs in the field of wireless power transfer (WPT) have made the prospects of charging EVs wirelessly increasingly viable (Bi et al. 2016; Kan et al. 2017; Lee et al. 2013; Li and Mi 2014; Liu and Song 2017). Advances in wireless charging technology are perhaps the missing key to unlock the future of mobility systems, WPT describes the transfer of electricity across an electromagnetic field and uses magnetic resonance induction to transfer electricity from charging pads embedded within the ground to a pad installed on the vehicle. Under laboratory conditions, WPT can charge at an efficiency close to 80–90%, providing a similar charging power (e.g., 6–30 kW) as the conventional plug-in method (Bi et al. 2016). Compared to plug-in, wireless charging offers greater flexibility in its application, allowing vehicles to charge in stationary mode called stationary wireless power transfer (SWPT) (i.e., when parked in garage or public parking spaces, and at traffic intersections) or dynamic mode called dynamic wireless power transfer (DWPT) (i.e., en route charging when vehicles are moving on roadways). Despite its current limited availability, many original equipment manufacturers (OEMs) of automobiles, such as Kia, BMW, Mercedes Benz, Nissan, General Motors, and Tesla, have already begun integrating wireless charging capability into EV designs. Other companies, such as Plugless and Qualcomm, offer wireless charging pads that will be compatible with various vehicle models (Bi et al. 2016; Plugless Power 2015).

In addition to convenience and increased charging availability, WPT offers opportunities for downsizing the expensive and heavy EV onboard battery thus reducing vehicle cost and weight, as well as improving vehicle fuel economy (Bi et al. 2015). Despite a growing body of literature dedicated to R&D of each emerging technology, respectively, little work explores the synergistic relationship between charging infrastructure and vehicle technologies in enhancing fleet performance and sustainable mobility, which poses a research gap. The Shared Autonomous Battery Electric Vehicle fleet can be regarded as a car-sharing fleet that is driverless and pure electric.

This study applies sustainability-based and life cycle framework to evaluate and demonstrate the synergies of the following four emerging technologies both qualitatively and quantitatively:

- Wireless charging technology
- Shared mobility services technology
- Autonomous driving technology
- Battery electric vehicle (BEV) technology

A wireless charging and shared autonomous battery electric vehicle (W+SABEV) system is modeled. First, an analytical framework is presented to assess the pros and cons of the emerging W+SABEV system vs. the conventional plug-in charging BEV system, adhering to the principles of sustainable mobility, and highlights the impacts and dynamics of the disruptive technologies on the key parameters that define sustainable mobility. Second, a quantitative analysis presents the synergies of the four technologies by modeling a W+SABEV system and demonstrates that the combination of the four technologies can shorten the payback time of greenhouse gas (GHG) emission burdens in terms of infrastructure and vehicles.

2 Qualitative analysis

2.1 Review of emerging technologies

A review of technologies is conducted based on a combination of literature review and a qualitative life cycle analysis of vehicle technologies. We derive a life cycle framework to evaluate the sustainability of proposed mobility systems based on the principles of green engineering (Anastas and Zimmerman 2003). We consider the in-use and upfront burdens for the cost, energy, and emissions of mobility systems, adopting a systems-level approach. Our framework serves as a general guideline to assess proposed mobility systems and technologies, highlighting notable trends that correspond to sustainable performance. Charging infrastructure utilization, vehicle utilization, and vehicle ownership are three trends that ultimately drive the sustainable performance of vehicle transportation (Sperling 2018).

The vehicle technologies and mode choices are predicted to shift dramatically (Fulton et al. 2017). A more in-depth summary of each mobility trend is provided as follows.

Shared mobility services Share mobility services include ride sharing, ride-hailing, and car sharing. This paper focuses on ride-hailing. Shared vehicle fleets increase the utilization of a given vehicle, as private cars are estimated to be unused (parked) a majority of the time; the increase in vehicle utilization offers opportunities to enhance both sustainability and mobility (Shoup 2017). Shared fleets can increase mobility for non-vehicle owners or populations no longer capable of driving. Shared mobility could also increase vehicle miles traveled due to rebound effect. From a sustainability objective, the reduction of on-road vehicles in conjunction with their increased utilization will lead to significant reductions in emissions, energy demands, and system-wide costs. It is worth noting that shared mobility services should complement, not compete against, existing transportation systems. The prospect of shared fleets is promising, but the transition away from private vehicle ownership will be gradual and likely limited in non-urban environments.

Vehicle autonomy and connectivity Connected and automated vehicles (CAV) technology allows for the real-time optimization of routes and charging decision-making. While only partial vehicle automation is currently commercially available, full-scale driverless vehicles are predicted to hit the market within the next five to 20 years (Anderson et al. 2014). CAV technology enhances mobility through the optimization of traffic flow, demand forecasting, and increase in mobility for users that cannot drive, to name a few. From a sustainability perspective, CAV technology has the potential to reduce emissions through platooning, more efficient driving, and the optimization of charging time and location (Bi et al. 2016). Research has also shown, however, that CAV technology may lead to an increase in VMT due to rebound effect from driving convenience and decrease in vehicle fuel efficiency due to the increase in weight from the CAV technology (Gawron et al. 2018). Nonetheless, vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication technologies allow for the data-driven, real-time operation of vehicles.

Powertrain technology Currently, there are internal combustion engine vehicles (ICEVs), with hybrid electric (HEV), plug-in hybrid electric (PHEV), and battery electric vehicles (BEV) representing the remaining mix. Bloomberg New Energy Finance anticipates that EVs will constitute 55% of new sales and represent 33% of the global fleet by 2040 (BloombergNEF 2018). Battery electric vehicles offer the greatest opportunity to reduce GHG emissions, where a vehicle's relative impact is dependent on electricity grid emissions (Zivin et al. 2014). The emission reductions between BEV and petroleum-based vehicle systems will only increase as renewable energy resources displace fossil fuel–based power generation.

Therefore, the shift towards shared mobility, vehicle autonomy, and electrified transportation is desirable for a future of sustainable mobility.

2.2 Synergies of the emerging technologies

2.2.1 Synergies of wireless charging and shared autonomous battery electric vehicles

Charging infrastructure decision-making requires that the synergies between vehicle technologies be explicitly considered. The advantages and disadvantages of each technology are summarized in Fig. 1.

By integrating wireless charging technology instead of the conventional plug-in charging technology to charge shared autonomous battery electric vehicles (SABEV), the pros of each technology can be enhanced, and some of the cons of each technology can be eliminated. The key synergies are summarized as follows.

Synergies between wireless charging and shared mobility services technologies On-road wireless charging can extend the operation time of shared fleets by recharging the battery incrementally, reducing the time and distance a vehicle must dedicate to maintain a minimum battery range. The spatial flexibility wireless charging provides aligns with the dynamic operations that shared fleets offer, highlighting the larger shift away from centralized vehicle infrastructure. Despite limited research that models shared autonomous fleets with respect to various charging scenarios, initial research indicates that wireless charging reduces both labor costs and non-passenger vehicle miles traveled (VMT), making shared, electric fleets

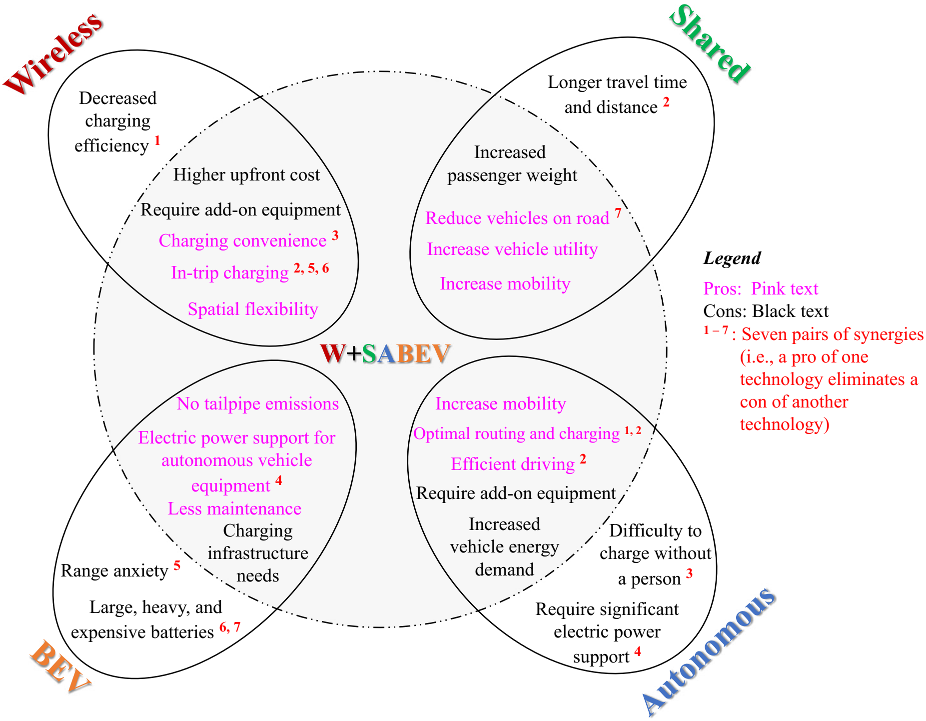

Fig. 1 Advantages and disadvantages of vehicle technologies that distinguish synergies of a wireless charging and shared autonomous battery electric vehicle (W+SABEV) fleet

financially competitive compared to shared internal combustion engine (ICE) fleets (Chen et al. 2016).

Synergies between wireless charging and autonomous driving technologies The benefits of both technologies are realized when deployed together. Wireless charging supports the full automation of vehicles as they can charge without the need of human intervention. Wireless charging also allows autonomous vehicles to strategically charge not only in parked spaces, but also at traffic lights and along the road when dynamic charging is considered. Vehicle autonomy is needed to realize the benefits of wireless charging for a variety of reasons. From a technical standpoint, an autonomous vehicle will maximize the charging efficiency by perfectly aligning the wireless charging pads. An autonomous vehicle offers communication between both vehicles and infrastructure. It can select optimal times and locations for charging by smart routing. An autonomous vehicle can also park itself and charge itself without any human intervention, reducing the amount of charging stations needed when vehicles are not in use. Research on SABEV systems has concluded that wireless charging increases operational efficiency, as vehicles can incrementally charge themselves throughout service (Chen et al. 2016; Fagnant and Kockelman 2014).

Synergies between wireless charging and BEV technologies Although the large-scale wireless charging infrastructure poses significant deployment burdens, it offers opportunities to downsize the expensive and heavy BEV battery by recharging it incrementally to still satisfy the desired vehicle range. Such trade-offs are most evident when modeling the relationship between vehicle battery size and charging station placement. With respect to fixed bus routes, the authors' previous study has shown that wireless charging for pure electric busses allows batteries to be 27–44% the size of a plug-in charged battery. This battery downsizing would result in lightweighting the vehicle and improving the fuel economy (Bi et al. 2015), as well as reduction in BEV costs. Wireless charging also offers spatial flexibility for charging infrastructure deployment, because it can be built on existing roads or parking spaces, without the need of procuring new lots to build plug-in charging stations. This would address the challenges of spatially constrained cities to supply adequate charging infrastructure.

2.2.2 System dynamics and key parameters for sustainability

Having shown the potential of wireless charging technology to enhance the sustainable mobility of SABEV systems, this section focuses on the dynamics of critical parameters, trade-offs, and constraints which define such systems. The system dynamics driven by the disruptive technologies are shown in Fig. 2. It is assumed that the system seeks to serve a fixed passenger travel demand in a given day. By penetrating the disruptive technologies into the system, there will be changes driven by that penetration, as highlighted in the figure. The results are a combination of both positive and negative feedbacks demonstrating the interconnected complexity of passenger travel demand, vehicle design, and infrastructure needs. Wireless charging can: (1) reduce the battery capacity due to more en route charging time and charger utility improvement by optimal siting of charging infrastructure; (2) reduce range anxiety due to more charging availability, therefore stimulating EV market share growth (Lin et al. 2014). As such, wireless charging serves as a catalyst to spark adoption trends and improve sustainable mobility; and (3) increase the production burden and weight of vehicles due to the add-on equipment of onboard wireless chargers. Shared mobility can increase the ridership which results in extra distance detoured to pick up and drop off the additional passengers and add-on vehicle weight from the additional passengers, but it would reduce the fleet size required to serve the same amount of passenger travel. Autonomous driving technology would

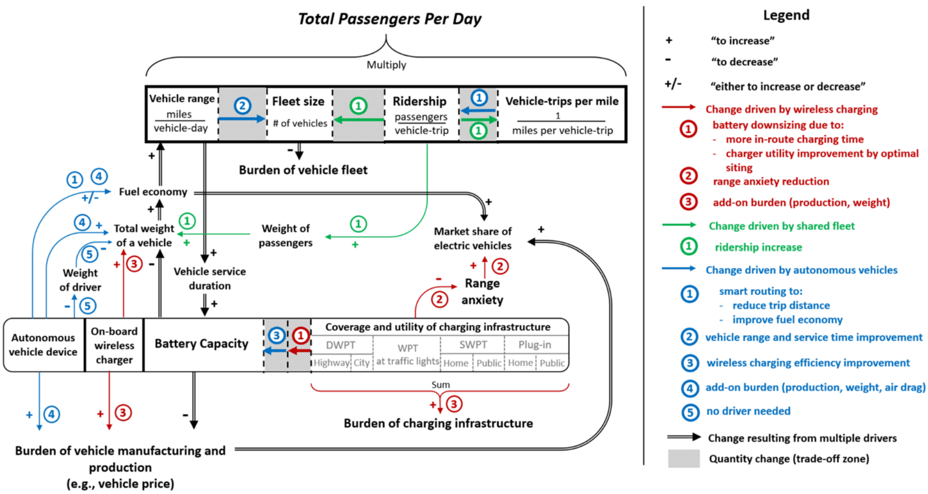

Fig. 2 System dynamics driven by the disruptive technologies

(1) reduce trip distance and improve fuel economy by smart routing; (2) improve vehicle range (miles traveled) and service time because of continuous operation of driverless vehicles as compared to a human-driving vehicle operation that may be interrupted by the driver's need to rest after a few hours of driving; (3) improve the wireless charging efficiency by aligning the onboard charging pads perfectly with the off-board charging pads by precisely detecting the location of the wireless charging transmitter coils on the ground; (4) increase the production burdens, weight, and air drag of the vehicles due to the add-on equipment of autonomous technology (e.g., Lidar and computing systems); and (5) reduce the vehicle weight due to no need of driver.

3 Quantitative analysis

3.1 System design

A life cycle model is developed to evaluate the synergistic effect of the four emerging technologies on the payback time of GHG emissions of infrastructure and vehicle burdens, by comparing a W+SABEV system (system #1) vs. a non-shared plug-in charging BEV system (system #2) serving the same fixed number of 12,500 passengers (hypothetical assumption) on a daily basis. The metric of GHG emissions is selected as an indicator of environmental sustainability performance in this study.

The GHG payback time is defined as the time when the additional burdens resulting from system #1 is equal to the cumulative savings of system #1, as compared to system #2. The additional burdens include (1) wireless charging infrastructure; (2) additional weight of passengers per vehicle-trip that add weight to vehicles; and (3) autonomous vehicle device. The additional savings include (1) fleet size reduction; (2) battery downsizing; (3) no driver weight (for shared fleets operated by transportation network companies); and (4) use-phase electricity savings. The emission factors of these burdens and savings are obtained from the literature (Argonne National Laboratory 2017; Bi et al. 2015; Gawron et al. 2018; Kim et al. 2016).

Key parameters of system #1 are varied to illustrate their impacts on the GHG payback time, number of vehicles needed, and average battery capacity of EVs, as shown in Table 1. The variation range of each key parameter is based on empirical estimate and the literature. Wireless charging utility factor is defined as the average percentage of time that a W+SABEV spends on charging relative to the entire trip duration, namely the probability that a W+SABEV encounters an available charging facility en route. Smart routing (eco-driving) factor

Table 1 Model setup for system comparison

Key parameters	System #1 (W+SABEV)	System #2 (Plug-in Charging BEV)
Wireless charging utility factor	5– 25%	N/A
Average ridership per BEV (U.S. Department of Transportation 2017)	1.5 passengers–2.25 passengers	1.5 passengers
DWPT efficiency (Bi et al. 2016)	65–80%	N/A*
Miles traveled per BEV per day	120 miles–180 miles	120 miles
Smart routing (eco-driving) factor (Gawron et al. 2018)	1.00–0.85	1.00

W+SABEV, wireless charging shared autonomous battery electric vehicles; *BEV*, battery electric vehicles; *DWPT*, dynamic wireless power transfer; *N/A*, not available

*Plug-in charging efficiency (grid-to-battery) is assumed to be 90%

is defined as the ratio of the trip distance after and before autonomous driving technology is employed, due to better speed control, routing, and platooning. The ridership is varied starting from 1.5 passengers per trip because it is assumed to operate in populated urban area.

Detailed model parameters and equations are documented in the Appendix.

3.2 GHG payback time

The impacts on GHG payback time, fleet size, and average battery capacity from individual technologies as well as all technologies in conjunction are shown in Fig. 3. The results indicate that deploying all of those technologies in conjunction would significantly decrease the GHG payback time, number of vehicles, and battery capacity. Individual technology alone would not achieve such a great reduction. However, it is also noted that shared mobility and smart routing (or eco-driving) are key drivers to reduction of GHG payback time due to the benefits of fleet size reduction and fuel efficiency improvement brought by each technology respectively. The increase of wireless charging utility factors will increase charging opportunity and time, so smaller battery capacities are needed; however, this alone is not enough to reduce GHG payback time. The increase of vehicle miles traveled per day for each EV would require a larger battery but would result in a reduction in number of vehicles.

Further analysis demonstrates the impact of wireless charging utility factor on the GHG payback time by evaluating an average W+SABEV fleet, as shown in Fig. 4. Compared to a plug-in charging BEV system, a W+SABEV system with wireless charging utility factor < = 5% will pay back GHG emission burdens of additional infrastructure deployment beyond 10 years; and a W+SABEV system with wireless charging utility factor more than or equal to 19% will pay back GHG emission burdens of additional infrastructure deployment within 5 years. The presented sustainability

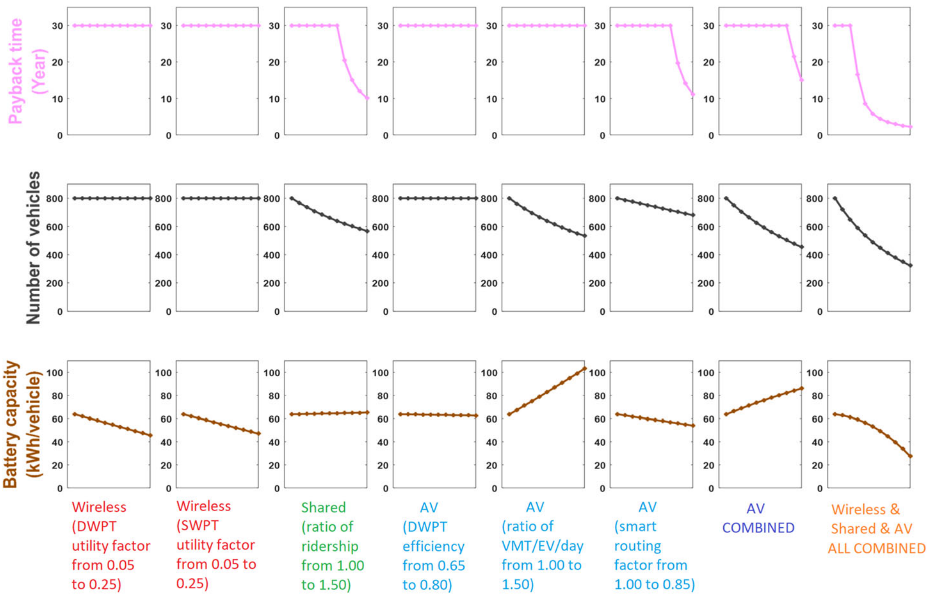

Fig. 3 Effect of each technology on the payback time, fleet size, and battery capacity. DWPT, dynamic wireless power transfer; SWPT, stationary wireless power transfer; VMT, vehicle miles traveled; EV, electric vehicle; AV, autonomous vehicle

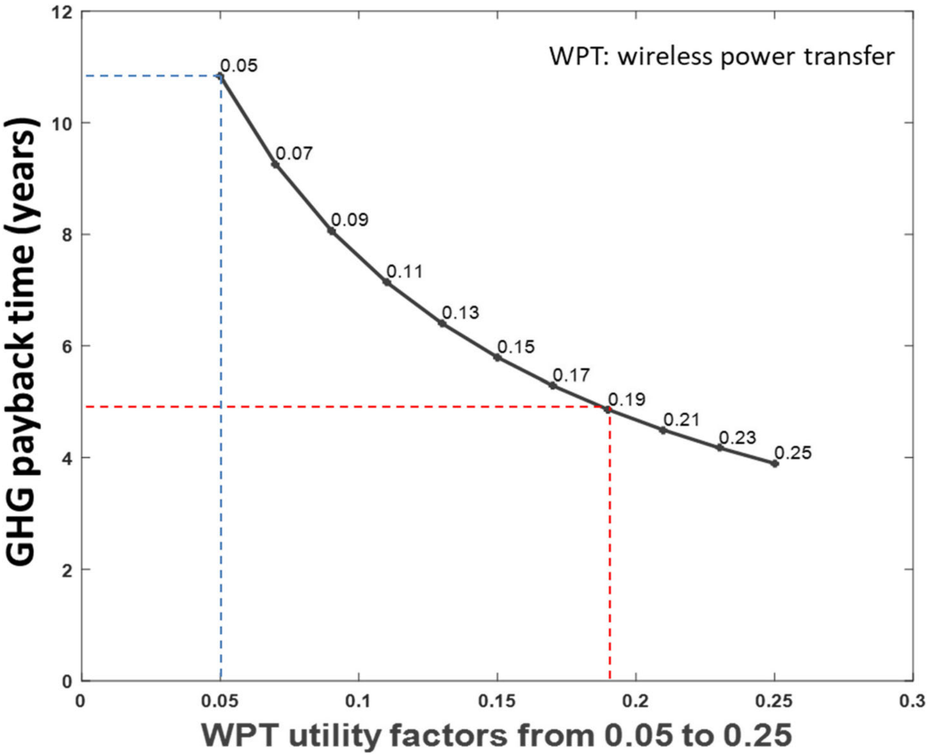

Fig. 4 Effect of wireless charging utility factor on the payback time. GHG, greenhouse gases; WPT, wireless power transfer

framework suggests that a high utilization of a given system is a fundamental requisite for its overall sustainability. Within the context of transportation systems, this implies that vehicle operation time and range should be maximized and charging infrastructure should be fully utilized through optimal deployment. This principle of utility maximization is essential so that the upfront burdens can be offset by in-use savings. This study models the future technologies and assumes that the autonomous driving device consumes an additional 10% of energy of a BEV, which is based on the prediction of future computing efficiency and energy performance of autonomous driving device. A sensitivity analysis is conducted to evaluate if a higher energy consumption by autonomous driving device would significantly increase the GHG payback time. It is found that when the wireless charging utility factor is above 15%, the payback time would only increase by about 2 to 4 years if the additional energy consumption is increased to 20% of total BEV energy use, but when the utility factor is lower than 15%, the payback time would be doubled or even tripled. Therefore, it also means a higher utility factor is very important for a promising payback time.

4 Conclusions and discussions

Much of the current literature focuses on the analysis of transportation systems and emerging technologies. While it is vital to develop individual emerging technology and improve its individual performance, it is equally important to recognize and assess the synergistic effects of the following emerging technologies and the interconnection between vehicle and infrastructure:

- Wireless charging technology
- Shared mobility services technology
- Autonomous driving technology
- Battery electric vehicle technology

Through both qualitative and quantitative analyses and a parametric model of a W+SABEV fleet, the synergistic effects of the four technologies are demonstrated in enhancing sustainability of future transportation and reducing payback of upfront GHG emission burdens from infrastructure and vehicles. Shared mobility and eco-driving are key drivers to reduction of GHG payback time due to the benefits of fleet size reduction and fuel efficiency improvement brought by each technology respectively. Results indicate that based on the status quo and predictions of technology development using 2018 data, compared to a plug-in charging BEV system:

- A W+SABEV system with wireless charging utility factor less than or equal to will pay back GHG emission burdens of additional infrastructure deployment beyond 10 years (so this is not optimal by any means, and this valley of death needs to be avoided at the very beginning of W+SABEV projects);
- A W+SABEV system with wireless charging utility factor more than or equal to 19% will pay back GHG emission burdens of additional infrastructure deployment within 5 years.

Globally, urbanization and growth in vehicle ownership pose significant sustainability challenges for decision makers to mitigate emissions and reduce energy consumption from the transportation sector. One way to address these challenges is to reduce vehicle ownership and improve fleet efficiency through shared mobility. Ride-hailing vehicles currently represents up to 5% of total passenger miles traveled (U.S. Department of Transportation 2017), and it is expected to continually gain more dominance. Wireless charging is becoming a promising solution for efficient operation of ride-hailing fleets, as indicated by a recent news announcement that wireless charging infrastructure is to be deployed for electric taxis in Oslo, Norway (Dzikiy 2019).

This study demonstrates that by integrating wireless charging, vehicle automation, and electrification into a ride-hailing fleet, the resulting synergies can reduce the number of vehicles needed by more than 50% while still serving the same travel demand. The efficiency and convenience elements realized through these emerging technologies during fleet operation are vital contributors in terms of mitigating overall GHG emissions and paying back the infrastructure GHG emission burdens.

There are a variety of applications of W+SABEV systems to shape future mobility and mitigate global impacts of transportation, for example, ride-hailing and taxi services, transit busses, and shuttle busses. In urbanized areas, shared mobility is gradually replacing travel by privately owned vehicles where W+SABEV systems can play an important role in driving sustainable mobility transformations.

Future work using agent-based modeling (ABM) approaches would be useful to characterize the real-world stochasticity. A deterministic life cycle model is developed in study to evaluate the synergistic effect of four emerging technologies to enhance sustainable mobility. The deterministic model is capable of characterizing the key parameters of the system, including vehicle miles traveled, average fuel economy, and battery downsizing. However, in the real world, there is stochastic effect from passenger travel demand and actual traffic congestion. By modeling passengers and vehicles as agents, further examination of the W+SABEV system by using ABM can inform decision-making in terms of optimizing the layout of wireless charging infrastructure to better serve the passenger travel demand within a region by shared mobility services. An ABM would also help investigate and provide more insights on the effect of randomness of passenger travel demand (e.g., origin, destination, and trip distance) on the reliability of the W+SABEV system. In addition, ABM approach can also incorporate the convenience benefits of stationary wireless charging at home or at work which eliminates the hassle of plugging in. Charging convenience can be quantitatively characterized by the monetary value of saved time. A policy analysis on the real-time pricing mechanisms can be conducted to examine the impact of different prices of electricity according to supply and demand on the vehicles' decisions on route choices so as to help regulate and decentralize congestion on wireless charging lanes. In this research, GHG is used as a sustainability indicator. Other metrics, such as costs, may have different patterns from the GHG results. In future work, the economic performance and synergies of W+SABEV systems can be evaluated by using a sophisticated economic and business model and calculating the payback of infrastructure investment costs from use-phase saving and revenues. Through ABM, future work can also incorporate the possible increase in vehicle miles traveled due to dead-heading and rebound effects.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Appendix

This Appendix provides detailed model equations and calculations. To compare the system performance of the base case of a plug-in charging BEV fleet vs. a W+SABEV fleet, it is assumed that both systems will provide mobility services for a fixed total passenger travel per day, i.e., $\Phi = 12500$ passengers per day, as shown in Eq. (1). Φ is a product of average number of passengers per trip ($\overline{n}_{\text{passenger}}$ for the base case and $\overline{n'}_{\text{passenger}}$ for the W+SABEV), average number of trips per vehicle per day ($\overline{n}_{\text{trip}}$ for the base case and $\overline{n'}_{\text{trip}}$ for the W+SABEV), and number of vehicles (n_{veh} for the base case and n'_{veh} for the W+SABEV). The average mileage per vehicle per day ($\overline{L}$ for the base case and $\overline{L}'$ for the W+SABEV) can be calculated using Eq. (2) to Eq. (5) with the average miles per trip ($\overline{d}_{\text{trip}}$

= 10 miles/trip), miles of detour per passenger ($\overline{d}_{\text{passenger}}$ = 1 mile/passenger), smart routing (eco-driving) factor θ, range extension factor β, and ridership factor κ.

$$\Phi = \overline{n}_{\text{passenger}}\overline{n}_{\text{trip}}n_{\text{veh}} = \overline{n'}_{\text{passenger}}\overline{n'}_{\text{trip}}n'_{\text{veh}} \tag{1}$$

$$\overline{L} = \frac{\Phi}{\overline{n}_{\text{passenger}}n_{\text{veh}}}\left(\overline{d}_{\text{trip}} + \overline{d}_{\text{passenger}}\overline{n}_{\text{passenger}}\right) \tag{2}$$

$$\beta = \frac{\overline{L}'}{\overline{L}} \tag{3}$$

$$\kappa = \frac{\overline{n'}_{\text{passenger}}}{\overline{n}_{\text{passenger}}} \tag{4}$$

$$\overline{L}' = \frac{\Phi}{\overline{n}'_{passenger}n'_{veh}}\left(\overline{d}_{trip} + \overline{d}_{passenger}\overline{n}'_{passenger}\right)\theta \tag{5}$$

The average BEV battery capacity for the base case c_{B} is defined by Eq. (6), where e is the average energy consumption rate of a battery electric vehicle (0.33 kWh/mile) and ε is the state of charge window (60%), i.e., the operating capacity relative to the nameplate capacity. The autonomous driving device consumes additional energy e_{AV}(kWh/mile), which is assumed to be a proportion ($\mu = 10\%$) of e, as shown in Eq. (7). The time of en route charging $\overline{T}_{\text{SWPT}}$ (hours of charging per vehicle per day) at SWPT charging spots can be calculated by multiplying the utility factor k_{SWPT} (probability of encountering a SWPT charging spot), number of stops at traffic intersections per day $\frac{\overline{L}'}{\overline{d}_{\text{stop}}}$ (where $\overline{d}_{\text{stop}}$ is the average distance between stops), and average stoppage time at a traffic intersection ($\overline{t}_{\text{SWPT}}$), as shown in Eq. (8). Similarly, the time of en route charging $\overline{T}_{\text{DWPT}}$ (hours of charging per vehicle per day) on DWPT charging lanes can be calculated by multiplying the utility factor k_{DWPT} (probability of driving on a DWPT lane) and total vehicle operating time per day $\frac{\overline{L}'}{\overline{v}}$ (where $\overline{v}$ is average vehicle speed), as shown in Eq. (9). The average battery capacity for a vehicle in the W+SABEV fleet c''_{B} can be calculated using Eq. (10) to Eq. (13). The base case battery capacity c_{B} needs to be adjusted by taking into account the following factors: (1) those en route charging ($\eta_{\text{SWPT}}\eta_{\text{B}}P\overline{T}_{\text{SWPT}}$ and $\eta_{\text{DWPT}}\eta_{\text{B}}P\overline{T}_{\text{DWPT}}$) can downsize the battery; (2) vehicle weight change resulting from battery weight change, equipment weight change, and passengers' weight change; and (3) energy consumption rate change due to vehicle weight change, smart driving, and additional energy consumption by autonomous driving device. η_{SWPT} is the SWPT grid-to-battery charging efficiency, η_{B} is the battery charge/discharge efficiency (90%), P is the actual power rate (30 kW), η_{DWPT} is the grid-to-battery DWPT charging efficiency, $c_{\text{B, min}}$ is the assumed minimum battery capacity (20 kWh), ρ is 0.156 kWh/kg of lithium ion battery of a

Tesla Model S, $\overline{\Delta}_e$ is the average change in energy consumption rate (kWh/mile),w_{person} is the average weight of a person (79 kg),w_{OW} is the weight of an onboard wireless charger (16 kg), w_{AV} is the weight of autonomous driving device (16–22 kg) (Gawron et al. 2018),w_{veh} is the weight of a base case vehicle (1595 kg), ϕ is the lightweighting correlation (6% energy consumption reduction per 10% vehicle weight reduction) (Bi et al. 2015), λ is a factor characterizing the energy saving due to smart routing (eco-driving) and better speed control of autonomous vehicles and is assumed to equal θ, e' is the energy consumption rate (kWh/mile) for a W+SABEV, c_{B}' is the intermediate calculated battery capacity for a W+SABEV, and c_{B}'' is the final calculated battery capacity of a W+SABEV.

$$c_{\text{B}} = \frac{\overline{L} \cdot e}{\varepsilon} \tag{6}$$

$$e_{\text{AV}} = e \cdot \mu \tag{7}$$

$$\overline{T}_{\text{SWPT}} = k_{\text{SWPT}} \cdot \frac{\overline{L}'}{\overline{d}_{\text{stop}}} \cdot \overline{t}_{\text{SWPT}} \tag{8}$$

$$\overline{T}_{\text{DWPT}} = k_{\text{DWPT}} \cdot \frac{\overline{L}'}{\overline{v}} \tag{9}$$

$$c_B' = \max\left\{ \frac{\left(\overline{L}' \cdot (e + e_{\text{AV}}) - \eta_{\text{SWPT}} \eta_B P \overline{T}_{\text{SWPT}} - \eta_{\text{DWPT}} \eta_B P \overline{T}_{\text{DWPT}}\right)}{\varepsilon}, c_{B,\min} \right\} \tag{10}$$

$$\overline{\Delta}_e = \frac{(c_B - c_B')/\rho + \left(w_{\text{person}} \overline{n}_{\text{passenger}} + w_{\text{person}}\right) - \left(w_{\text{person}} \overline{n}'_{\text{passenger}} + w_{\text{OW}} + w_{\text{AV}}\right)}{w_{\text{veh}}} \cdot \phi \cdot e \tag{11}$$

$$e' = \lambda \cdot \left(e - \overline{\Delta}_e\right) \tag{12}$$

$$c_B'' = \max\left\{ \frac{\overline{L}' \cdot (e' + e_{\text{AV}}) - \eta_{\text{SWPT}} \eta_B P \overline{T}_{\text{SWPT}} - \eta_{\text{DWPT}} \eta_B P \overline{T}_{\text{DWPT}}}{\varepsilon}, c_{B,\min} \right\} \tag{13}$$

Finally, the breakeven time τ (days) is calculated by letting $f_{\text{net}} = f_{\text{burdens}} - f_{\text{savings}} = 0$ and solving Eq. (14) to Eq. (19). f_{net},f_{burdens}, and f_{savings} are the cumulative net emissions (kg CO_2-eq), additional burdens of W+SABEV infrastructure and device (kg CO_2-eq), and additional savings of W+SABEV (kg CO_2-eq), respectively.n_{SWPT} is number of traffic intersections with

SWPT and ζ_{DWPT} is the total mileage of DWPT lanes. $\sigma_{\mathrm{SWPT,\ base}}$ (453 kg CO_2-eq), $\sigma_{\mathrm{DWPT,\ base}}$ (1,184,000 kg CO_2-eq/lane-mile), and $\sigma_{\mathrm{OW,\ base}}$ (103 kg CO_2-eq) are the burdens of a 6 kW (P_{base}) wireless charger (Bi et al. 2015) and σ_{AV} (1300 kg CO_2-eq) is the burden of an autonomous vehicle device (Gawron et al. 2018). $\bar{l}$ is the actual average length of SWPT at a traffic intersection and l_{base} is the base length (10 m). s_{V} is the savings from fleet size reduction (kg CO_2-eq), s_{B} is the battery savings (kg CO_2-eq), and s_{E} is the electricity savings (kg CO_2-eq). σ_{veh} is the vehicle production and manufacturing burden without battery (7000 kg CO_2-eq) (Kim et al. 2016) and σ_{B} is the battery production and manufacturing burden (32.64 kg CO_2-eq/kWh) (Bi et al. 2015). η_{PC} is the plug-in charging efficiency from grid-to-battery (90%). $\overline{\sigma}_{\mathrm{E,night}}$ and $\overline{\sigma}_{\mathrm{E,day}}$ are average nighttime and daytime electricity emission intensities (kg CO_2-eq/kWh), respectively (U.S. EPA 2016).

$$f_{\mathrm{net}} = f_{\mathrm{burdens}} - f_{\mathrm{savings}} \tag{14}$$

$$\begin{aligned} f_{\mathrm{burdens}} = {} & n_{\mathrm{SWPT}}\sigma_{\mathrm{SWPT,base}}\frac{P}{P_{\mathrm{base}}}\frac{\bar{l}}{l_{\mathrm{base}}} + \zeta_{\mathrm{DWPT}}\sigma_{\mathrm{DWPT,base}}\frac{P}{P_{\mathrm{base}}} + n'_{\mathrm{veh}}\sigma_{\mathrm{OW,base}}\frac{P}{P_{\mathrm{base}}} \\ & + n'_{\mathrm{veh}}\sigma_{\mathrm{AV}} \end{aligned} \tag{15}$$

$$f_{\mathrm{savings}} = s_V + s_B + s_E \cdot \tau \tag{16}$$

$$s_V = n_{\mathrm{veh}}\sigma_{\mathrm{veh}} - n'_{\mathrm{veh}}\sigma_{\mathrm{veh}} \tag{17}$$

$$s_B = n_{\mathrm{veh}}c_B\sigma_B - n'_{\mathrm{veh}}c''_B\sigma_B \tag{18}$$

$$s_E = n_{\mathrm{veh}}\frac{\overline{L}\cdot e}{\eta_{PC}\eta_B}\cdot\overline{\sigma}_{\mathrm{E,night}} - n'_{\mathrm{veh}}\left[P\left(\overline{T}_{\mathrm{SWPT}} + \overline{T}_{\mathrm{DWPT}}\right)\cdot\overline{\sigma}_{\mathrm{E,day}} + \frac{\overline{L}'\cdot(e' + e_{\mathrm{AV}}) - \eta_{\mathrm{SWPT}}\eta_B P\overline{T}_{\mathrm{SWPT}} - \eta_{\mathrm{DWPT}}\eta_B P\overline{T}_{\mathrm{DWPT}}}{\eta_{\mathrm{SWPT}}\eta_B}\cdot\overline{\sigma}_{\mathrm{E,night}}\right] \tag{19}$$

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Affiliations

Zicheng Bi[1] · Michael A. Reiner[1] · Gregory A. Keoleian[1] · Yan Zhou[2] · Michael Wang[2] · Zhenhong Lin[3]

1 School for Environment and Sustainability, University of Michigan, Ann Arbor, MI 48109, USA

2 Systems Assessment Center, Energy Systems Division, Argonne National Laboratory, Lemont, IL 60439, USA

3 Oak Ridge National Laboratory, National Transportation Research Center, Knoxville, TN 37932, USA